

# MEASUREMENT OF THE TOP QUARK MASS

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The first evidence<sup>1</sup> and subsequent discovery<sup>2,3</sup> of the top quark was reported nearly 4 years ago. Since then, CDF and D0 have analyzed their full Run 1 data samples, and analysis techniques have been refined to make optimal use of the information. In this paper, we report on the most recent measurements of the top quark mass, performed by the CDF and D0 collaborations at the Fermilab Tevatron. The CDF collaboration has performed measurements of the top quark mass in three decay channels from which the top quark mass is measured to be  $175.5 \pm 6.9 \text{ GeV}/c^2$ . The D0 collaboration combines measurements from two decay channels to obtain a top quark mass of  $172.1 \pm 7.1 \text{ GeV}/c^2$ . Combining the measurements from the two experiments, assuming a  $2 \text{ GeV}/c^2$  correlated systematic uncertainty, the measurement of the top quark mass at the Tevatron is  $173.9 \pm 5.2 \text{ GeV}/c^2$ . This report presents the measurements of the top quark mass from each of the decay channels which contribute to this measurement.

## 1 Introduction

The top quark is defined as the  $I_3 = +1/2$  member of a weak SU(2) isodoublet that also contains the  $b$  quark. In  $p\bar{p}$  collisions, top quarks are produced primarily in  $t\bar{t}$  pairs and are expected to decay through the electroweak interaction to a W-boson and b-quark. In the standard model, the branching fraction for  $t \rightarrow Wb$  is expected to be nearly 100%. The decay width<sup>4</sup> is calculated to be 1.6 – 1.7 GeV for masses between 150 – 180 GeV/c<sup>2</sup>. The top quark mass is sufficiently large that top-flavored hadrons are not expected to form<sup>5</sup>.

The top quark mass,  $M_{top}$ , is an important parameter in calculations of electroweak processes since its mass is approximately 35 times larger than that of the next heaviest fermion. Like other fermions, its mass is taken to be an unpredicted parameter of the standard model<sup>6</sup>. Calculations of electroweak radiative corrections relate the top quark and the W-boson ( $M_W$ ) masses to that of the Higgs boson. Precision measurements of  $M_{top}$  and  $M_W$  can therefore aid in searches for the Higgs boson.

## 2 Overview of Top Quark Mass Measurement

In  $\sqrt{s} = 1.8$  TeV  $p\bar{p}$  collisions, top quarks are expected to be produced in pairs mainly through the subprocess  $q\bar{q} \rightarrow t\bar{t}$ . At the Tevatron, both CDF and D0 select samples of events which are consistent with containing a  $t\bar{t}$  pair. Since each W-boson may decay leptonically or hadronically, this leads to three categories of events. Events which have 2 high  $P_T$  isolated leptons (both W-bosons decay leptonically), missing transverse energy ( $E_T$ )<sup>7</sup> and two or more jets (from the b-quarks) are classified as *Dilepton* events. Events which have one isolated high  $P_T$  lepton,  $E_T$ , and 4 or more jets are referred to as *l+jets* events. Events containing 6 or more jets and no high  $P_T$  isolated leptons are classified as *All-hadronic* events. Neither CDF nor D0 try to reconstruct the top mass from candidate  $t\bar{t} \rightarrow \tau + X$  events. Ignoring final states containing  $\tau$ 's, the branching ratio for  $t\bar{t}$  into these three decay channels is 5%, 30%, and 44% respectively.

Both CDF and D0 have measured the top quark mass in the Dilepton and l+jets channels. CDF has also made a measurement of the top quark mass in the All-Hadronic channel. A general procedure is used for extracting the top quark mass. For each decay channel, we choose a variable (or a set of variables) which can be measured in the data sample, and is highly correlated with  $M_{top}$ . Examples of such variables include event-by-event top mass, jet  $E_T$ ,  $E_T$ , total scalar  $E_T$ , etc. The distribution of a given variable is modelled using Monte Carlo (MC) simulations of  $t\bar{t}$  signal and background. The  $t\bar{t}$  signal distributions are modelled using the HERWIG<sup>8</sup> MC simulation and are produced for a wide range of input top quark masses, ranging from  $\approx 120$  to 220 GeV/c<sup>2</sup>. Background distributions are derived from a combination of Monte Carlo and/or data, depending on the channel. The modelled signal and background distributions are generically referred to as *templates*. The top quark mass is extracted from a maximum likelihood procedure which compares the observed data distribution(s) to the  $t\bar{t}$  signal and background templates. Assumptions made in the modelling of signal and background are included as sources of systematic uncertainty.

## 3 Top Quark Mass Measurement in the Dilepton Topology

Both CDF<sup>9</sup> and D0<sup>10</sup> have reported measurements of the top quark mass in the Dilepton decay topology. Because these events are presumed to have two neutrinos, the kinematics of the  $t\bar{t}$  system (including the top quark mass) cannot be uniquely determined. A measurement of the top quark mass can however be made by comparing the measured observables with the expectation from  $t\bar{t}$  and background. Each experiment employs two techniques to measure the top quark mass from their respective samples.

### 3.1 CDF Dilepton Mass Measurements

The first Dilepton mass measurement uses the energies of the 2 highest  $E_T$  jets in the candidate events as a discriminator for the top quark mass measurement. From a sample of 8 events, with an expected background of  $1.1 \pm 0.3$  events, the analysis yields a top quark mass of  $159 \pm 23(\text{stat}) \pm 11(\text{syst}) \text{ GeV}/c^2$ . A second analysis exploits the fact that, in the W-boson rest frame of the  $t \rightarrow Wb$  decay, the top quark mass can be related to the invariant mass of the b-jet and lepton ( $M_{lb}$ ) to which it decays. Among the two possible pairings of the 2 leptons with the 2 highest  $E_T$  jets, the pair with the smaller sum of invariant masses is chosen. From this analysis, the top quark mass is measured to be  $163 \pm 20(\text{stat}) \pm 6(\text{syst}) \text{ GeV}/c^2$ . The jet energy scale, and signal and background modelling dominate the systematic uncertainty. The two measurements are combined taking into account the correlations in uncertainties to obtain a top quark mass of  $161 \pm 17(\text{stat}) \pm 10(\text{syst}) \text{ GeV}/c^2$ .

### 3.2 D0 Dilepton Mass Measurements

Both techniques which D0 employs uses MC simulations to calculate a probability that the observed kinematics of the event are consistent with top of an assumed mass. This probability is mapped out as a function of assumed top mass in the range from 80 to 280  $\text{GeV}/c^2$ . The probability in the first technique is based on: (a) the probability for the charged leptons to have come from  $t\bar{t}$  decay at the assumed mass, and (b) the probability for the event to have been produced by valence quarks with momentum fractions  $f(x)$  and  $f(\bar{x})$ . The second technique calculates a probability based on the difference between the measured and calculated  $\cancel{E}_T$  in the event. The calculation of the  $\cancel{E}_T$  is facilitated by assuming values for the pseudorapidity of the two neutrinos ( $\eta_1$  and  $\eta_2$ ), and then integrating over the  $\eta_1, \eta_2$  phase space. For both techniques, detector resolution effects are included as well as trying both lepton-(b-quark) combinations. Based on the data sample of 6 events and an expected background of 1.42 events, the mass is measured to be  $168.1 \pm 12.4(\text{stat}) \pm 3.6(\text{syst}) \text{ GeV}/c^2$  using the first technique, and  $169.9 \pm 14.8(\text{stat}) \pm 3.6(\text{syst}) \text{ GeV}/c^2$  using the second technique. The dominant systematics are the same as those mentioned for the CDF dilepton analyses. The measurements are combined to obtain a top quark mass of  $168.4 \pm 12.3(\text{stat}) \pm 3.6(\text{syst}) \text{ GeV}/c^2$ .

## 4 Top Quark Mass Measurement in the l+jets Topology

Both CDF<sup>11</sup> and D0<sup>12</sup> have measured the top quark mass in the l+jets topology. The l+jets decay channel currently allows for the most accurate determination of the top quark mass. The measurement benefits from a relatively large branching ratio and the ability to fully reconstruct the top mass on an event-by-event basis. The momentum of all final state particles are assumed to be measured, with the exception of the unobserved neutrino,  $\nu$ . The transverse momentum components of the neutrino however can be inferred from the  $\cancel{E}_T$  in the event, leaving only its Z-component unmeasured. Three kinematic constraints are implied by the  $t\bar{t} \rightarrow l\nu q\bar{q}b\bar{b}X$  decay hypothesis. Namely, we require that  $M_{l\nu} = M_W$ ,  $M_{jj} = M_W$ , and  $M_{l\nu b} = M_{j\bar{j}b}$ , where  $b = b$  or  $\bar{b}$  jet,  $j = \text{non-}b$  jet,  $M_W = \text{W-boson mass}$ , and  $M_{xx(x)}$  are invariant masses formed from the reconstructed 4-vectors of the indicated objects. Because  $t\bar{t}$  events are expected to contain 2 b-quarks, as compared to only a few percent for background events, identifying b-jets improves the signal to background ratio (S/B). B-jets are tagged by either reconstructing the secondary decay vertices of B-hadrons (SVX tagged jet), or by identifying charged tracks which are consistent with coming from semileptonic b-hadron decay (SLT tagged jet). Each event is fit to the  $t\bar{t} \rightarrow l\nu q\bar{q}b\bar{b}X$  topology, requiring b-tagged jets to be assigned to b-quarks, All allowable permutations are tried, and the top mass corresponding to the solution with the lowest  $\chi^2 < 10$  is taken as the reconstructed top mass ( $M_{rec}$ ) for a given event. The ensemble of reconstructed

masses (one per event) are fit using a likelihood procedure to extract the best estimate of the top quark mass.

#### 4.1 CDF $l+jets$ Mass Measurement

The initial sample selection requires 1 isolated lepton with  $P_T > 20$  GeV/c,  $|\eta| < 1$ ,  $\cancel{E}_T > 20$  GeV,  $\geq 3$  jets with  $E_T > 15$  GeV,  $|\eta| < 2.0$ , and a fourth jet with  $E_T > 8$  GeV and  $|\eta| < 2.4$ . After applying these selection criteria and the  $\chi^2$  cut on the kinematic fit, the sample consists of 151 events, of which  $\approx 35\%$  are estimated to be from  $t\bar{t}$ . Motivated by the different S/B and top mass resolution for events with SVX, SLT, or no tags, MC simulations were used to determine an optimal way to partition the sample as to obtain the best precision on the top quark mass measurement<sup>13</sup>. Studies showed that an optimal partitioning consists of subdividing the events into the four statistically independent categories shown in Table 1. The table shows the numbers of events in each subsample, the expected background fraction<sup>14</sup>  $x_b$ , and the fitted top mass.

Data Sample	#Events	$x_b(\%)$	Top Mass (GeV/c <sup>2</sup> )
SVX Double (2 SVX tagged jets)	5	$5^{+4}_{-2}$	$170.1 \pm 9.3$
SVX Single (1 SVX tagged jet)	15	$13^{+5}_{-4}$	$178.0 \pm 7.9$
SLT tagged ( $\geq 1$ SLT tagged jets, no SVX tags)	14	$40^{+9}_{-9}$	$142.1^{+33}_{-14}$
No Tags ( $\geq 4$ jets with $E_T > 15$ GeV, $ \eta  < 2.0$ )	42	$56^{+14}_{-17}$	$180.8 \pm 9.0$
Combined	76	-	$175.9 \pm 4.8$

Table 1: Subsamples used in the top quark mass analysis, expected background fractions, and the measured top quark mass in each sample. The last line shows the results from the combined likelihood fit to all four subsamples.

Since the four subsamples are statistically independent, the joint likelihood for the 76 events is given by the product of the four subsample likelihoods. Each subsample likelihood uses parameterized signal and background probability densities, along with a constraint on the the background fraction (see Table 1), to evaluate the likelihood for observing the measured set of masses as a function of the top mass. The results of the likelihood fit for each subsample and the combined result are shown in Table 1. The results of the combined fit for the 76 data events and are shown in Fig. 1. Including the systematic uncertainties presented in Table 3, the top quark mass is measured to be  $175.9 \pm 4.8(\text{stat.}) \pm 4.9(\text{syst.})$  GeV/c<sup>2</sup> for events in the  $l+jets$  topology.

#### 4.2 D0 $l+jets$ Mass Measurement

The event selection for the D0 analysis is similar to CDF. The main differences are a larger  $|\eta|$  cut for the charged lepton (from the W-boson decay) and all four jets are required to have  $E_T > 15$  GeV. After the event selection criteria and the kinematic  $\chi^2$  cut, 77 events remain of which 5 are SLT tagged (D0 did not have a silicon vertex detector in Run 1). D0 extends the likelihood procedure by including an additional variable  $D$

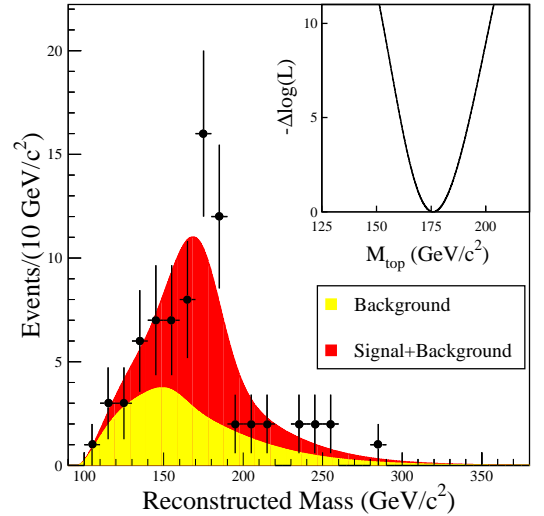


Figure 1: The results of applying the likelihood procedure to the combined subsamples. The figure shows the data (points), fitted background (light shaded region), and fitted signal plus background (darker shaded region). The inset shows the shape of  $-\log \mathcal{L}$  versus the generated top mass from which we extract the best estimate of the top mass and the statistical uncertainty.

which provides discrimination between signal and background events. Two versions of the discriminant are tried. The first is a low-bias version  $D_{lb}$ , and the second,  $D_{NN}$ , was the output from a neural network trained on  $t\bar{t}$  signal and background events. Both discriminants provide similar levels of discrimination between signal and background events. Two-dimensional signal templates of  $D$  vs  $M_{rec}$  are generated for many input values for the top mass and a single template for the background. For each top mass value, a likelihood is minimized with respect to the number of signal and background events. The corresponding negative log-likelihood values are fit to a quadratic function of top mass, and the measured top mass is taken to be where the function is a minimum. The fits to the data are presented in Table 2 and shown in Fig. 2. For illustrative purposes, the data sample is separated into (a) signal depleted and (b) signal enhanced subsamples. Also shown are the likelihood fits for the two methods. Including the systematic uncertainties shown in Table 3, the top quark mass is measured to be  $173.3 \pm 5.6(\text{stat.}) \pm 5.5(\text{syst.})$   $\text{GeV}/c^2$ .

Method	$M_{top}$ ( $\text{GeV}/c^2$ )	Fitted $N_s$	Fitted $N_b$
LB	$174.0 \pm 5.6$	$24 \pm 8$	$53 \pm 10$
NN	$171.3 \pm 6.0$	$29 \pm 9$	$48 \pm 10$
LB+NN	$173.3 \pm 5.6$	-	-

Table 2: Fit results using the low-bias (LB) likelihood, then neural-network (NN) method, and the combined result. Shown are the fitted top quark masses, and the fitted number of signal ( $N_s$ ) and background ( $N_b$ ) events.

## 5 CDF All-Hadronic Top Mass Measurement

This measurement<sup>15</sup> requires 6 or more jets with  $E_T > 15$   $\text{GeV}$ , and  $|\eta| < 2$ , and at least one b-tagged jet. Additional cuts, based on MC simulations, were employed to improve the S/B ratio. An event-by-event top mass is evaluated using the measured jet energies and the kinematic constraints mentioned previously. All thirty combinations are tried, and the top mass having the lowest  $\chi^2 < 10$  is taken as the top mass for the event. The data sample consists of 136 events, of which  $108 \pm 9$  events are expected to come from background sources. A likelihood procedure (with a gaussian background constraint) was used to extract a measured top mass of  $186 \pm 10(\text{stat.}) \pm 12(\text{syst.})$   $\text{GeV}/c^2$ . The systematic uncertainties are dominated by the jet energy scale signal modelling, and the fitting method.

## 6 Combining the top mass measurements

The measurement in each decay topology may be combined to improve the resolution on the top quark mass measurement. Each experiment combines their measurements into a single measurement, taking into account correlations in uncertainties between the measurements. Combining

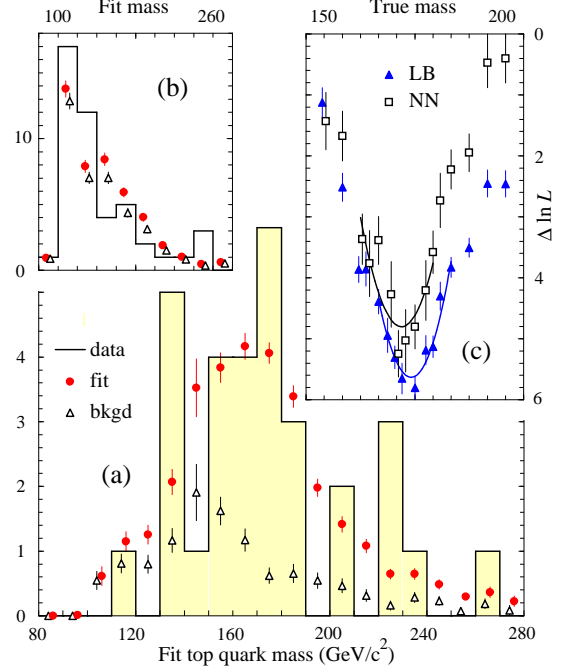


Figure 2: The fit results from the LB and NN likelihood procedures applied to the 77 event data sample. (a) Events which have  $D_{lb} > 0.43$  and (b)  $D_{lb} < 0.43$ . The histogram shows the data, and the points are the MC fit results. (c) shows the fit to  $-\log L$  vs top mass for the two methods.

Source	CDF	D0
Energy Scale	4.4	4.0
Signal Model	1.8	1.9
Background	1.3	2.5
Noise/M.I.	-	1.3
b-tagging bias	0.4	-
Likelihood Method	-	1.3
Total	4.9	5.5

Table 3: Main systematic uncertainties ( $\text{GeV}/c^2$ ) in the l+jets top quark mass measurement for each experiment. (M.I.=Multiple Interactions; PDF's = Parton Distribution Functions)

the three CDF measurements, the top quark mass is measured to be  $175.6 \pm 6.8 \text{ GeV}/c^2$ . The two D0 measurements yield a top quark mass of  $172.1 \pm 7.1 \text{ GeV}/c^2$ . These two mass measurements

are combined assuming a  $2 \text{ GeV}/c^2$  correlated systematic uncertainty. The top quark mass at the Tevatron is therefore measured to be  $173.9 \pm 5.2 \text{ GeV}/c^2$ . The values of  $M_W$  versus  $M_{top}$  for several (standard model) Higgs masses are shown in Fig. 3. The data tend to favor a mass below  $\approx 500 \text{ GeV}/c^2$ , but clearly more data is needed to reduce the uncertainties. In Run 2, we expect to measure  $M_{top}$  to within  $1\text{-}2 \text{ GeV}/c^2$  and  $M_W$  to within  $40 \text{ MeV}/c^2$ . This will clearly narrow the search window for future Higgs' searches.

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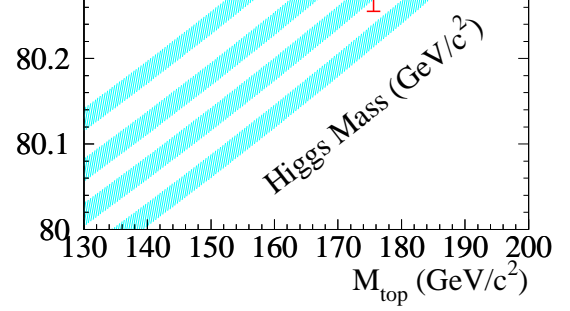


Figure 3:  $M_W$  versus  $M_{top}$  for various choices of the Higgs mass. Shown are the CDF and D0 averages, as well as the world average.